

GROUP III NITRIDE LED WITH
UNDOPED CLADDING LAYER (5000.137)

FIELD OF THE INVENTION

6,534,797
This application incorporates entirely by reference
co-pending and commonly-assigned application Ser. No.
09/706,057 filed November 3, 2000 for *Group III Nitride*
5 *Light Emitting Devices with Gallium-Free Layers*.

The present invention relates to semiconductor
structures of light emitting devices, particularly light
emitting diodes and laser diodes formed from Group III
nitrides, which are capable of emitting light in the red to
10 ultraviolet portions of the electromagnetic spectrum.

BACKGROUND OF THE INVENTION

Photonic semiconductor devices fall into three
categories: devices that convert electrical energy into
optical radiation (e.g., light emitting diodes and laser
15 diodes); devices that detect optical signals (e.g.,
photodetectors); and devices that convert optical radiation
into electrical energy (e.g., photovoltaic devices and
solar cells). Although all three kinds of devices have
useful applications, the light emitting diode may be the
20 most commonly recognized because of its application to
various consumer products and applications.

Light emitting devices (e.g., light emitting diodes
and laser diodes), herein referred to as LEDs, are
photonic, p-n junction semiconductor devices that convert
25 electrical power into emitted light. Perhaps most
commonly, LEDs form the light source in the visible portion

of the electromagnetic spectrum for various signals, indicators, gauges, and displays used in many consumer products (e.g., audio systems, automobiles, household electronics, and computer systems). LEDs are desirable as
5 light output devices because of their generally long lifetime, their low power requirements, and their high reliability.

Despite widespread use, LEDs are somewhat functionally constrained, because the color that a given LED can produce
10 is limited by the nature of the semiconductor material used to fabricate the LED. As well known to those of ordinary skill in this and related arts, the light produced by an LED is referred to as "electroluminescence," which represents the generation of light by an electric current
15 passing through a material under an applied voltage. Any particular composition that produces electroluminescent light tends to do so over a relatively narrow range of wavelengths.

The wavelength of light (i.e., its color) that can be
20 emitted by a given LED material is limited by the physical characteristics of that material, specifically its bandgap energy. Bandgap energy is the amount of energy that separates a lower-energy valence band and a higher energy conduction band in a semiconductor. The bands are energy
25 states in which carriers (i.e., electrons or holes) can reside in accordance with well-known principles of quantum mechanics. The "bandgap" is a range of energies between the conduction and valence bands that are forbidden to the carriers (i.e., the carriers cannot exist in these energy

states). Under certain circumstances, when electrons and holes cross the bandgap and recombine, they will emit energy in the form of light. In other words, the frequency of electromagnetic radiation (*i.e.*, the color) that can be
5 produced by a given semiconductor material is a function of that material's bandgap energy.

In this regard, narrower bandgaps produce lower energy, longer wavelength photons. Conversely, wider bandgap materials produce higher energy, shorter wavelength
10 photons. Blue light has a shorter wavelength—and thus a higher frequency—than most other colors in the visible spectrum. Consequently, blue light must be produced from transitions that are greater in energy than those transitions that produce green, yellow, orange, or red
15 light. Producing photons that have wavelengths in the blue or ultraviolet portions of the visible spectrum requires semiconductor materials that have relatively large bandgaps.

The entire visible spectrum runs from the violet at or
20 about 390 nanometers to the red at about 780 nanometers. In turn, the blue portion of the visible spectrum can be considered to extend between the wavelengths of about 425 and 480 nanometers. The wavelengths of about 425 nanometers (near violet) and 480 nanometers (near green) in
25 turn represent energy transitions of about 2.9 eV and about 2.6 eV, respectively. Accordingly, only a material with a bandgap of at least about 2.6 eV can produce blue light.

Shorter wavelength devices offer a number of advantages in addition to color. In particular, when used

in optical storage and memory devices, such as CD-ROM optical disks, shorter wavelengths enable such storage devices to hold significantly more information. For example, an optical device storing information using blue
5 light can hold substantially more information in the same space as one using red light.

The basic mechanisms by which light-emitting diodes operate are well understood in this art and are set forth, for example, by Sze, *Physics of Semiconductor Devices*, 2d
10 Edition (1981) at pages 681-703.

The common assignee of the present patent application was the first in this field to successfully develop commercially viable LEDs that emitted light in the blue color spectrum and that were available in large, commercial
15 quantities. These LEDs were formed in silicon carbide, a wide-bandgap semiconductor material. Examples of such blue LEDs are described in U.S. Patent Nos. 4,918,497 and 5,027,168 to Edmond each titled "Blue Light Emitting Diode Formed in Silicon Carbide." Other examples of Group III
20 nitride LED structures and laser structures are described in commonly assigned U.S. Patents Nos. 5,523,589; 5,592,501; and 5,739,554.

In addition to silicon carbide, candidate materials for blue light emitting devices are gallium nitride (GaN) and its associated Group III (i.e., Group III of the
25 periodic table) nitride compounds such as aluminum gallium nitride (AlGaN), indium gallium nitride (InGaN), and aluminum indium gallium nitride (AlInGaN). These materials are particularly attractive because they offer direct

energy transitions with bandgaps between about 1.9 to about 6.2 eV at room temperature. More common semiconductor materials such as silicon, gallium phosphide, or gallium arsenide are unsuitable for producing blue light because
5 their bandgaps are approximately 2.26 eV or less, and in the case of silicon, are indirect semiconductors and inefficient light emitters.

As known to those familiar with LEDs and electronic transitions, a direct transition occurs in a semiconductor
10 when the valence band maxima and the conduction band minima have the same momentum state. This means that crystal momentum is readily conserved during recombination of electrons and holes so that the energy produced by the transition can go predominantly and efficiently into the
15 photon, (*i.e.*, to produce light rather than heat). When the conduction band minimum and valence band maximum do not have the same momentum state, a phonon (*i.e.*, a quantum of vibrational energy) is required to conserve crystal momentum and the transition is called "indirect." The
20 necessity of a third particle, the phonon, makes indirect radiative transitions less likely, thereby reducing the light emitting efficiency of the device.

Generally speaking, an LED formed in a direct bandgap material will perform more efficiently than one formed in
25 an indirect bandgap material. Therefore, the direct transition characteristics of Group III nitrides offer the potential for brighter and more efficient emissions—and thus brighter and more efficient LEDs—than do the emissions from indirect materials such as silicon carbide.

Accordingly, much interest in the last decade has also focused on producing light emitting diodes in gallium nitride and related Group III nitrides.

Although Group III nitrides offer a direct transition
5 over a wide bandgap energy range, the material presents a particular set of technical manufacturing problems. In particular, no commercially-viable technique has yet emerged for producing bulk single crystals of gallium nitride (GaN) that are capable of functioning as
10 appropriate substrates for the gallium nitride epitaxial layers on which photonic devices would be formed.

All semiconductor devices require some kind of structural substrate. Typically, a substrate formed of the same material as the active region offers significant
15 advantages, particularly in crystal growth and lattice matching. Because gallium nitride has yet to be formed in such bulk crystals, gallium nitride photonic devices must be formed in epitaxial layers on non-GaN substrates.

Recent work in the field of Group III nitride
20 substrates includes copending and commonly assigned U.S. patent applications Serial Nos. 09/361,945, filed July 27, 1999, for "Growth of Bulk Single Crystals of Aluminum Nitride;" 09/361,944 filed July 27, 1999, for "Growth of Bulk Single Crystals of Aluminum Nitride from a Melt;"
25 09/111,413 filed July 7, 1999, for "Growth of Bulk Single Crystals of Aluminum Nitride;" 09/169,385 filed October 9, 1998, for "Growth of Bulk Single Crystals of Aluminum Nitride: Silicon Carbide Alloys;" and 09/154,363 filed September 16, 1998 for "Vertical Geometry In GaN LED." All

of these pending applications are incorporated entirely herein by reference.

Using different substrates, however, causes an additional set of problems, mostly in the area of crystal lattice matching. In nearly all cases, different materials have different crystal lattice parameters. As a result, when a gallium nitride epitaxial layer is grown on a different substrate, some crystal lattice mismatching and thermal expansion coefficient mismatching will occur. The resulting epitaxial layer is referred to as being "strained" by this mismatch. Crystal lattice mismatches, and the strain they produce, introduce the potential for crystal defects. This, in turn, affects the electronic characteristics of the crystals and the junctions, and thus tends to degrade the performance of the photonic device. These kinds of defects are even more problematic in high power structures.

In early Group III nitride LEDs, the most common substrate for gallium nitride devices was sapphire (*i.e.*, aluminum oxide Al_2O_3). Certain contemporary Group III nitride devices continue to use it.

Sapphire is optically transparent in the visible and ultraviolet ranges, but has a crystal lattice mismatch with gallium nitride of about 16 percent. Furthermore, sapphire is insulating rather than conductive, and is unsuitable for conductivity doping. Consequently, the electric current that must be passed through an LED to generate the light emission cannot be directed through a sapphire substrate. Thus, other types of connections to the LED must be made.

In general, LEDs with vertical geometry use conductive substrates so that ohmic contacts can be placed at opposite ends of the device. Such vertical LEDs are preferred for a number of reasons, including their easier manufacture and simpler incorporation into end-use devices than non-vertical devices. In the absence of a conductive substrate, however, vertical devices cannot be formed.

In contrast with sapphire, Gallium nitride only has a lattice mismatch of about 2.4 percent with aluminum nitride (AlN) and mismatch of about 3.5 percent with silicon carbide. Silicon carbide has a somewhat lesser mismatch of only about 1 percent with aluminum nitride.

Group III ternary and quaternary nitrides (e.g., indium gallium nitride and aluminum indium gallium nitride) have also been shown to have relatively wide bandgaps. Accordingly, such Group III nitride solid solutions also offer the potential for blue and ultraviolet semiconductor lasers and LEDs. These compounds, however, present the same problems as gallium nitride, namely, the lack of an identical single crystal substrate. Thus, each is typically used in the form of epitaxial layers grown on different substrates. This presents the same potential for crystal defects and associated electronic problems.

Accordingly, the assignee of the present invention has developed the use of silicon carbide substrates for gallium nitride and other Group III devices as a means of solving the conductivity problems of sapphire as a substrate. Because silicon carbide can be doped conductively, vertical LEDs can be formed. As noted, a vertical structure

facilitates both the manufacture of LEDs and their incorporation into circuits and end-use devices.

As known to those familiar with Group III nitrides, their properties differ based on the identity and mole fraction of the present Group III elements (e.g., gallium, aluminum, indium). For example, increasing the mole fraction of aluminum tends to increase the bandgap, while decreasing the amount of aluminum tends to increase the refractive index. Similarly, a larger proportion of indium will decrease the bandgap of the material, thus permitting the bandgap to be adjusted or "tuned" to produce photons of desired frequencies. Changing the molar proportions in the solutions also changes the crystal lattice spacing. Accordingly, and despite much effort in this area, a need still exists for devices that incorporate vertical geometry, and that take advantage of the characteristics that result when the proportions of indium, aluminum, and gallium are desirably adjusted in the active layers, cladding layers, and buffer layers of Group III nitride photonic devices.

It is a further object of the present invention to provide light emitting devices having decreased nonradiative recombination and improved efficiency.

OBJECT AND SUMMARY OF THE INVENTION

Therefore, it is an object of the present invention to produce light emitting diodes and laser diodes from Group III nitrides in a manner that takes advantage of their favorable properties.

5 The invention meets these objects via a semiconductor structure that includes a Group III nitride active layer positioned between a first n-type Group III nitride cladding layer and a second n-type Group III nitride cladding layer. The active layer has a bandgap that is smaller than the respective bandgaps of the first and second n-type cladding layers. The semiconductor structure further includes a p-type Group III nitride layer, which is positioned in the semiconductor structure such that the
10 second n-type cladding layer is between the p-type layer and the active layer.

15 In another embodiment, the second n-type Group III nitride cladding layer has a graded composition such that it is substantially lattice matched to the p-type Group III nitride layer at the junction with the p-type Group III nitride layer.

20 In another embodiment, the structure includes a third n-type Group III nitride layer positioned between the second n-type Group III nitride clad layer and the p-type Group III nitride layer. The third n-type Group III nitride layer preferably comprises the same material structure as the p-type Group III nitride layer such that a p-n homojunction is formed between the third n-type Group III nitride layer and the p-type Group III nitride layer.

25 The foregoing, as well as other objectives and advantages of the invention and the manner in which the same are accomplished, is further specified within the following detailed description and its accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a cross-sectional schematic view of the aspects of a semiconductor structure for a light emitting device according to the present invention;

5 Figure 2 is a plot of bandgap energy versus lattice parameter for Group III nitrides alloys of aluminum, indium, and gallium (assuming a linear interpolation);

Figure 3 is a cross-sectional schematic view of an embodiment of the semiconductor structure;

10 Figure 4 is a cross-sectional schematic view of an embodiment of the semiconductor structure;

Figure 5 is a cross-sectional schematic view of an embodiment of the semiconductor structure;

15 Figure 6 is a cross-sectional schematic view of an embodiment of the semiconductor structure;

Figure 7 is a cross-sectional schematic view of an embodiment of the semiconductor structure;

Figures 8 and 9 are bandgap diagrams corresponding to certain prior art devices; and

20 Figures 10-12 are bandgap diagrams for devices according to the present invention.

DETAILED DESCRIPTION

The present invention is a semiconductor structure for light emitting devices that can emit in the red to
25 ultraviolet portion of the electromagnetic spectrum. The structure includes a Group III nitride active layer

positioned between a first n-type Group III nitride cladding layer and a second n-type Group III nitride cladding layer. The second n-type cladding layer is characterized by the substantial absence of magnesium (i.e., magnesium may be present, but only in amounts that are so small as to have no functional effect on the semiconductor device). The semiconductor structure itself is further characterized by a p-type Group III nitride layer, which is positioned in the semiconductor structure such that the second n-type cladding layer is between the p-type layer and the active layer. In addition, the active layer has a bandgap that is smaller than each respective bandgap of the first and second n-type cladding layers. As used herein, the term "layer" generally refers to a single crystal epitaxial layer.

A particular conductivity type (i.e., n-type or p-type) may be unintentional, but is more commonly a result of specifically doping the Group III nitrides using the appropriate donor or acceptor atoms. It is desirable to include layers of opposite conductivity types in order to form a p-n junction in the device. Under forward voltage bias, minority carriers injected across the p-n junction recombine to produce the desired luminescent emissions. Appropriate doping of Group III nitrides is well understood in the art and will not be further discussed herein other than as necessary to describe the invention.

In general, the active layer and the cladding layers comprise Group III-nitride compounds. The Group III

elements in such compounds may be aluminum, indium, gallium, or a combination of two or more such elements.

As will be understood by those having ordinary skill in the art, the molar fraction of aluminum, indium, and gallium in the active layer, the first n-type cladding layer, and the second n-type cladding layer may be generally expressed by the formula, $\text{Al}_x\text{In}_y\text{Ga}_{1-x-y}\text{N}$, where $0 \leq x \leq 1$ and $0 \leq y < 1$ and $(x + y) \leq 1$. In this regard, the relative concentrations of aluminum, indium, and gallium may vary from layer to layer. It will be understood by those skilled in the art, however, that a cladding layer cannot be indium nitride (*i.e.*, $y = 1$) because InN has the lowest bandgap of all possible combinations and the active layer cannot be aluminum nitride (*i.e.*, $x = 1$) because AlN has the highest bandgap of all possible combinations. It will be understood in these embodiments that the cladding layers will have a larger energy band gap than the active layer.

An understanding of the invention may be achieved with reference to Figure 1, which is a cross-sectional schematic view of a semiconductor structure for an LED according to the present invention. The semiconductor structure, which is generally designated at 10, includes a first n-type cladding layer 11 of $\text{Al}_x\text{In}_y\text{Ga}_{1-x-y}\text{N}$, where $0 \leq x \leq 1$ and $0 \leq y < 1$ and $(x + y) \leq 1$.

The semiconductor structure 10 also includes a second n-type cladding layer of $\text{Al}_x\text{In}_y\text{Ga}_{1-x-y}\text{N}$, where $0 \leq x \leq 1$ and $0 \leq y < 1$ and $(x + y) \leq 1$, or in a more specific embodiment,

an indium-free aluminum gallium nitride n-type cladding layer 12 having the formula, $\text{Al}_x\text{Ga}_{1-x}\text{N}$, where $0 < x < 1$. In this regard, the range for the variable x excludes both 0 and 1, which will be understood by those skilled in the art as requiring the presence of both aluminum and gallium (i.e., an alloy of aluminum and gallium). As noted, the second n-type cladding layer 12 specifically excludes magnesium, and may be doped or undoped. The cladding layers may be unintentionally n-type, i.e. undoped.

10 An n-type active layer 13 having the formula $\text{Al}_x\text{In}_y\text{Ga}_{1-x-y}\text{N}$, where $0 \leq x < 1$ and $0 \leq y \leq 1$ and $(x + y) \leq 1$, is positioned between the first n-type cladding layer and the second n-type cladding layer 12. In a more specific embodiment, the active layer 13 is aluminum-free, consisting essentially of an indium gallium nitride having the formula, $\text{In}_y\text{Ga}_{1-y}\text{N}$, where $0 < y < 1$. In this regard, the range for the variable y excludes both 0 and 1, which will be understood by those skilled in the art as requiring the presence of both indium and gallium (i.e., an alloy of indium and gallium).

20 The semiconductor structure is further characterized by a p-type Group III nitride layer 18, which as previously noted, is positioned in the semiconductor structure such that the second n-type cladding layer 12 is between the p-type layer 18 and the active layer 13. In preferred embodiments, the p-type layer is made of gallium nitride (preferably magnesium-doped gallium nitride); indium nitride; or indium gallium nitride of the formula $\text{In}_x\text{Ga}_{1-x}\text{N}$, where $0 < x < 1$.

Note that in embodiments wherein the p-type layer 18 is made of magnesium-doped gallium nitride, the second n-type cladding layer 12 should be thick enough to deter migration of magnesium from the p-type layer 18 to the active layer 13, yet thin enough to facilitate recombination of electrons and holes in the active layer 13. This helps to maximize emissions from the active layer 13. Moreover, because the p-n junction is not formed at the interface between an InGaN layer and an AlGaN layer -- i.e. an InGaN/AlGaN p-n junction is avoided - the interface should have a reduced density of interface states. Such a reduction in interface states should result in more efficient recombination of carriers in the active layer, with a corresponding increase in overall device efficiency.

In another embodiment, the p-type layer comprises a p-type superlattice formed of selectively doped p-type Group III nitride layers selected from the group consisting of gallium nitride; indium nitride; and indium gallium nitride of the formula $\text{In}_x\text{Ga}_{1-x}\text{N}$, where $0 < x < 1$. In particular, the superlattice is best formed from alternating layers of any two of these Group III nitride layers. In such a superlattice, alternating layers of gallium nitride and indium gallium nitride are most preferred.

The active layer 13 may be doped or undoped. As is known to those familiar with Group III nitride properties, the undoped material will generally be unintentionally n-type, and that is the case for the second n-type cladding layer 12. In particular, the first n-type cladding layer 11 and the second n-type cladding layer 12 have respective

bandgaps that are each larger than the bandgap of the active layer 13.

The Group III mole fractions can be selected to provide these characteristics. For example, Figure 2
5 theoretically describes bandgap energy versus lattice parameter. The triangular region of Figure 2 represents the range of bandgap energies available for Group III nitrides of aluminum, indium, and gallium. Figure 2 reveals that for any particular lattice parameter,
10 eliminating gallium maximizes the bandgap energy (*i.e.*, the bandgap for an aluminum indium nitride is defined by the AlN-InN segment).

As is known to those familiar with semiconductor structures—especially laser structures, the active layer
15 must have a lower bandgap than the adjacent n-type cladding layers, and a higher refractive index than the adjacent cladding layers. Such a structure gives two benefits important for laser capability. First, if the active layer has the lowest bandgap, it may form a quantum well into
20 which carriers tend to fall. This helps to enhance the device efficiency. Second, waveguiding occurs in the material that has the highest refractive index in the structure. Accordingly, when the bandgap of the active layer is less than that of the adjacent layers and its
25 refractive index is greater than that of the adjacent layers, the lasing capabilities of the device are enhanced.

Moreover, as known to those of ordinary skill in this art, the composition of ternary and quaternary Group III nitrides can affect both their refractive index and their

bandgap. Generally speaking, a larger proportion of aluminum increases the bandgap and decreases the refractive index. Thus, in preferred embodiments, in order for the cladding layers 11 and 12 to have a bandgap larger than the active layer 13 and a refractive index smaller than the active layer 13, the cladding layers 11 and 12 preferably have a higher fraction of aluminum or gallium as compared to the active layer 13. The larger bandgap of the cladding layers 11 and 12 encourages carriers to be confined in the active layer 13, thereby increasing the efficiency of the device. Similarly, the lower refractive index of the heterostructure layers 11 and 12 encourages the light to be more preferably guided along (*i.e.*, confined to) the active layer 13.

As previously noted, the recited variables (*e.g.*, x and y) refer to the structural layer they describe. That is, the value of a variable with respect to one layer is immaterial to the value of the variable with respect to another layer. For example, in describing the semiconductor structure, the variable x may have one value with respect to first n-type cladding layer 11, another value with respect to second n-type cladding layer 12, and yet another value with respect to active described layer 13. As will also be understood by those of ordinary skill in the art, the limitation $0 \leq (x + y) \leq 1$ in the expression $\text{Al}_x\text{In}_y\text{Ga}_{1-x-y}\text{N}$ simply requires that the Group III elements and the nitride be present in a 1:1 molar ratio.

In preferred embodiments, active layer 13 comprises an InGaN layer having a mole fraction of indium between about

0.05 and 0.55. Referring to Figs. 1 and 3, layer 12 is preferably an $\text{Al}_x\text{Ga}_{1-x}\text{N}$ layer having a mole fraction of aluminum between about 0.14 and 0.24, while layer 11 is preferably an $\text{Al}_x\text{Ga}_{1-x}\text{N}$ layer having a mole fraction of aluminum between about 0 and 0.15. Referring to Fig. 3, layer 19 is preferably an $\text{Al}_x\text{Ga}_{1-x}\text{N}$ layer having a mole fraction of aluminum between about 0 and 0.15.

It will be appreciated by those of ordinary skill in the art that, as used herein, the concept of one layer being "between" two other layers does not necessarily imply that the three layers are contiguous (*i.e.*, in intimate contact). Rather, as used herein the concept of one layer being between two other layers is meant to describe the relative positions of the layers within the semiconductor structure. Similarly, as used herein, the concept of a first layer being in contact with a second layer, "opposite" a third layer, merely describes the relative positions of the first and second layers within the semiconductor structure.

That said, in preferred embodiments of the semiconductor structure, the active layer 13 has a first surface 14 contiguous to the first n-type cladding layer 11 and a second surface 15 contiguous to the second n-type cladding layer 12. In other words, in such embodiments, the active layer 13 is sandwiched directly between the first n-type cladding layer 11 and the second n-type cladding layer 12, with no additional layers disturbing this three-layer isotype heterostructure (*i.e.* a heterostructure in which all of the materials have the same

conductivity type), which is designated by the bracket 16. In another preferred embodiment, the p-type layer 18 is in contact with said second n-type cladding layer 12, opposite said active layer 13.

5 The structural designation "heterostructure" is used in a manner well understood in this art. Aspects of these structures are discussed, for example, in Sze, *Physics of Semiconductor Devices*, Second Edition (1981) at pages 708-710. Although the cited Sze discussion refers to lasers,
10 it nonetheless illustrates the nature of, and the distinction between, homostructure, single heterostructure, and double heterostructure devices. Isotype heterostructures are discussed by Hartman et al. in U.S. Patent No. 4,313,125, which is hereby incorporated herein
15 in its entirety.

 The semiconductor device may also include additional n-type layers of $\text{Al}_x\text{In}_y\text{Ga}_{1-x-y}\text{N}$, where $0 \leq x \leq 1$ and $0 \leq y < 1$ and $(x + y) \leq 1$. In one embodiment depicted in Figure 3, a
20 third n-type layer 19 is positioned between second n-type cladding layer 12 and p-type layer 18. Preferably, the third n-type layer 19 has a first surface that is in contact with the p-type layer 18 and a second surface that is in contact with second n-type cladding layer 12.

 Third n-type layer 19 is lattice matched with p-type
25 layer 18. Preferably, third n-type layer 19 forms a p-n homojunction with p-type layer 18. Having a p-n homojunction reduces the number of interface states at the junction. Because such states may result in nonradiative

recombination, reducing the number of such states improves the recombination efficiency, thus improving overall device efficiency.

5 The semiconductor device 10 can further comprise a silicon carbide substrate 17 that has the same conductivity type as first n-type cladding layer 11 (*i.e.*, an n-type silicon carbide substrate). The silicon carbide substrate 17 preferably has a polytype of 3C, 4H, 6H, or 15R. The first n-type cladding layer 11 is positioned between the
10 silicon carbide substrate 17 and the active layer 13. In one embodiment of the invention, the silicon carbide substrate 17 is in contact with the first n-type cladding layer 11, opposite the active layer 13 (*i.e.*, there are no intervening layers between silicon carbide substrate 17 and
15 first n-type cladding layer 11).

The silicon carbide substrate 17 is most preferably a single crystal. As is well understood by those of ordinary skill in this art, a high quality single crystal substrate provides a number of structural advantages that in turn
20 provide significant performance and lifetime advantages. The silicon carbide substrate 17 can be formed by the methods described in U.S. Pat. No. 4,866,005 (now U.S. Patent No. RE 34,861). Preferably, the silicon carbide substrate 17 and the first cladding layer 11 are n-type.

25 In a preferred embodiment depicted by Figure 4, the first n-type cladding layer 11 has a first surface 21 that is in contact with the silicon carbide substrate 17 and a second surface 22 that is in contact with the active layer 13. In particular, the composition of the first n-type

cladding layer 11 is progressively graded such that the crystal lattice at its first surface 21 more closely matches the crystal lattice of the silicon carbide 17, and the crystal lattice at its second surface 22 more closely matches the crystal lattice of the active layer 13. A sufficient mole fraction of indium should be present in the first n-type cladding layer 11 to ensure that it remains conductive at its first surface 21, adjacent to the silicon carbide substrate 17.

As will be understood by those of ordinary skill in the art, progressively grading embraces both step grading and linear grading. Accordingly, as used herein, the concept of more closely matching respective crystal lattices does not imply perfect matching, but rather that a layer whose composition has been progressively, compositionally graded so that its lattice at a layer interface is more compatible with the crystal lattice of the adjacent layer. When fabricating devices, a number of considerations must be balanced, one of which is lattice matching. If other factors are more important, a perfect or close lattice match may be less important, and vice versa.

In this regard, n-type cladding layers, especially aluminum indium nitride n-type cladding layers, can be selectively lattice matched to gallium-containing active layers, especially gallium nitride and indium gallium nitride active layers, in order to reduce strain and defects. In particular, aluminum indium nitrides are useful because they can be lattice matched to other Group

III nitrides with lower bandgaps and therefore are useful as cladding layer materials. See Figure 2.

As will be understood by those having ordinary skill in the art, lattice matching of the cladding layers and the active layer can be a one-sided lattice match (i.e., where a lattice match occurs on one side of the active layer) or a two-sided lattice match (i.e., where a lattice match occurs on both sides of the active layer).

In another embodiment depicted by Figure 5, the semiconductor structure further includes a conductive buffer layer 23 positioned between the silicon carbide substrate 17 and the first n-type cladding layer 11. In a variant of this embodiment, the conductive buffer layer 23 is sandwiched between the silicon carbide substrate 17 and the first n-type cladding layer 11, with no intervening layers. The conductive buffer layer 23 preferably consists essentially of aluminum gallium nitride having the formula $\text{Al}_x\text{Ga}_{1-x}\text{N}$, where $0 < x < 1$. Alternatively, when the first n-type cladding layer 11 consists essentially of aluminum indium nitride having the formula, $\text{Al}_x\text{In}_{1-x}\text{N}$, where $0 < x < 1$, the conductive buffer layer 23 preferably consists essentially of aluminum indium nitride having the formula, $\text{Al}_x\text{In}_{1-x}\text{N}$, where $0 < x < 1$. Other acceptable buffers and buffer structures include those described in commonly assigned U.S. Patent Nos. 5,523,589, 5,393,993, and 5,592,501, the contents of each hereby being incorporated entirely herein by reference.

To facilitate the transition between the first n-type cladding layer 11 and the conductive buffer layer 23, the

semiconductor structure can further include a Group III nitride transition layer 24, preferably formed of gallium nitride, that is positioned between the conductive buffer layer 23 and the first n-type cladding layer 11. See
5 Figure 6. The transition layer 24 has the same conductivity type as the first n-type cladding layer 11 (i.e., an n-type transition layer).

Alternatively, as depicted by Figure 7, the conductive buffer layer 23 and transition layer 24 can be replaced by
10 discrete crystal portions 28 that are disclosed more fully in commonly assigned U.S. Patent Application Serial No. 08/944,547, filed October 7, 1997, now U.S. Patent No. _____, for "Group III Nitride Photonic Devices on Silicon Carbide Substrates with Conductive Buffer
15 Interlayer Structure," which is incorporated entirely herein by reference.

In yet another embodiment, the semiconductor structure
10 further includes a first ohmic contact 25 and a second ohmic contact 26. As indicated in Figure 1, the first ohmic contact 25 is positioned in the semiconductor
20 structure such that the silicon carbide substrate 17 is between the first ohmic contact 25 and the first n-type cladding layer 11. The second ohmic contact 26 is positioned in the semiconductor structure such that the p-
25 type layer 18 is between the second ohmic contact 26 and the second n-type cladding layer 12.

Preferably, the first ohmic contact 25 is placed directly on the silicon carbide substrate 17, opposite the first n-type cladding layer 11 (or opposite the conductive

buffer layer 23 or discrete crystal portions 28, depending on the particular structural embodiment), and the second ohmic contact 26 is placed directly on the p-type layer 18, opposite the second n-type cladding layer 12. In a variant
5 of this embodiment, the p-type layer 18 is sandwiched between the second ohmic contact 26 and a second p-type layer (not shown).

As recognized by those of ordinary skill in this art, the conductive buffer layer 23 provides a physical and
10 electronic transition between the silicon carbide substrate 17 and the first n-type cladding layer 11. In many circumstances, the presence of the conductive buffer layer 23 helps ease the physical strain that can result from the lattice differences between the silicon carbide substrate
15 17 and the first n-type cladding layer 11. Furthermore, to preserve the vertical function of the device, the conductive buffer layer 23 has to be sufficiently conductive to carry the desired or required current to operate the semiconductor device 10. Likewise, the
20 transition layer 24 serves a similar physical and electronic transition.

The ohmic contacts 25 and 26, which complete the advantageous vertical structure of the invention, are preferably formed of a metal such as aluminum (Al), nickel
25 (Ni), titanium (Ti), gold (Au), platinum (Pt), vanadium (V), alloys, or blends thereof, or sequential layers of two or more of these metals, but also may be formed of other ohmic contact materials known by those skilled in the art provided that they exhibit ohmic character and do not

otherwise interfere with the structure or function of the light-emitting device 10.

To the extent that the first ohmic contact 25 is formed to the silicon carbide substrate 17, the invention is distinguished from those devices that employ sapphire. Sapphire cannot be made conductive, and so cannot be connected to an ohmic contact. Consequently, sapphire-based devices cannot be formed into the kinds of vertical structures that are most preferred for LEDs.

Accordingly, in one preferred embodiment the invention is a semiconductor structure for light emitting devices that includes an n-type single crystal silicon carbide substrate 17 of a 3C, 4H, 6H, or 15R polytype; a p-type layer 18 formed of at least one Group III nitride selected from the group consisting of gallium nitride (preferably magnesium-doped gallium nitride), indium nitride, and indium gallium nitride having the formula $\text{In}_x\text{Ga}_{1-x}\text{N}$, where $0 < x < 1$; an undoped active layer of $\text{Al}_x\text{In}_y\text{Ga}_{1-x-y}\text{N}$, where $0 \leq x < 1$ and $0 \leq y \leq 1$ and $(x + y) \leq 1$; a first n-type cladding layer 11 of $\text{Al}_x\text{In}_y\text{Ga}_{1-x-y}\text{N}$, where $0 \leq x \leq 1$ and $0 \leq y < 1$ and $(x + y) \leq 1$; and a second n-type cladding layer 12 of $\text{Al}_x\text{In}_y\text{Ga}_{1-x-y}\text{N}$, where $0 \leq x \leq 1$ and $0 \leq y < 1$ and $(x + y) \leq 1$. Most preferably, the p-type layer 18 comprises a superlattice formed from alternating layers of any two of the aforementioned Group III nitrides.

As disclosed previously, the first n-type cladding layer 11 and the second n-type cladding layer 12 have respective bandgaps that are each larger than the bandgap

of the active layer 13. Moreover, the first n-type cladding layer 11 is positioned between the silicon carbide substrate 17 and the active layer 13, the second n-type cladding layer 12 is positioned between the active layer 13 and the p-type layer 18, and the active layer 13 is positioned between the first n-type cladding layer 11 and the second n-type cladding layer 12.

The composition of the first n-type cladding layer 11 can be progressively graded such that the crystal lattice at its first surface 21 more closely matches the crystal lattice of the silicon carbide 17, and the crystal lattice at its second surface 22 more closely matches the crystal lattice of the active layer 13. Similarly, the composition of the second n-type cladding layer 12 can be progressively graded such that the crystal lattice at its second surface more closely matches the crystal lattice of the p-type layer 18. As previously noted, progressively grading across an epitaxial layer embraces both grading in steps and grading continuously (*i.e.*, without steps). Causing the n-type cladding 12 to be substantially lattice matched to the p-type layer 18 reduces the number of interface states at the p-n junction formed between the layers. Because such states may result in nonradiative recombination, reducing the number of such states improves the recombination efficiency, thus improving overall device efficiency in the active layer 13.

Furthermore, and in accordance with the previous descriptions, this preferred structure may also include one or more of the following layers—a third n-type cladding

layer 19, the conductive buffer layer 23, the Group III nitride transition layer 24, the discrete crystal portions 28, and the ohmic contacts 25 and 26. In this regard, the conductive buffer layer 23 most preferably is aluminum
5 gallium nitride having the formula $\text{Al}_x\text{Ga}_{1-x}\text{N}$, where $0 \leq x \leq 1$.

Figures 8, 9, 10, 11 and 12 are bandgap diagrams of various structures, including embodiments of the present invention. All of the bandgap diagrams 8 through 12
10 represent the bandgaps under forward bias (i.e. "flat-band" conditions). It will be understood by a skilled person that the bandgap diagrams 8 through 12 are schematic in nature and are not necessarily drawn to scale. While they illustrate important aspects of the invention, it will be
15 understood that the actual band structure may vary slightly from the illustration. In Figures 8-12, whenever possible, identical numerical designations will refer to identical portions of the diagrams.

Figure 8 is a bandgap diagram of a prior art device
20 showing an n-type gallium nitride clad layer 30, an indium gallium nitride active layer 31, and a p-type aluminum gallium nitride layer 32. In this device, the p-n junction is represented by the dotted line at 33.

With respect to the physical structure of the device
25 and the interface quality between layers, interfaces between identical materials are the easiest to make of high quality. Among the Group III nitrides, the interface between gallium nitride and gallium nitride is the easiest to make of high quality, with the interface between gallium

nitride and aluminum gallium nitride being more difficult,
but easier than most others. The next-to-worst is the
interface between gallium nitride and indium gallium
nitride, with the worst interface quality being typically
5 demonstrated between indium gallium nitride and aluminum
gallium nitride.

Furthermore, it will be recalled that the
disassociation temperature of indium gallium nitride is
generally less than all of the other Group III nitrides.
10 Accordingly, once the InGaN active layer has been grown,
the growth temperatures for the remaining layers must be
limited to temperatures that avoid undesired disassociation
or degradation of the indium gallium nitride layer. Stated
differently, if the InGaN active layer were absent, the
15 AlGaN and GaN layers could be grown at higher temperatures
that are more favorable (all other factors being equal) for
higher quality epitaxial layers of these materials.

As a result, at the lower growth temperatures used to
grow the aluminum gallium nitride layers that are required
20 to protect the indium gallium nitride layer, the resulting
quality of the aluminum gallium nitride layers is somewhat
less than it would be if the layers could be grown at a
higher temperature.

Accordingly, although ordinarily an AlGaN-AlGaN
25 interface would be considered to make a good homojunction,
under the lower growth temperatures required to protect the
desired indium gallium nitride active layer of the present
invention, the aluminum gallium nitride layers are of poor
quality, with the p-type aluminum gallium nitride layers

being particularly bad. As a result, for devices that incorporate indium gallium nitride active layers, interfaces and junctions between p-type aluminum gallium nitride and n-type aluminum gallium nitride, are generally of very low quality. Thus the invention's avoidance of such junctions is counterintuitive and produces an unexpectedly better device. Stated differently, prior art devices that incorporate the structure of Figure 8 require interfaces between Group III nitrides that are difficult to form with high quality.

Figure 9 illustrates a device described in copending and commonly assigned application Serial No. 09/154,363 filed September 16, 1998. As in Figure 8, the n-type gallium nitride layer is designated at 30, the indium gallium nitride active layer is at 31, the p-n junction is at 33, and the p-type aluminum gallium nitride is designated at 32. The device illustrated in Figure 9, however, also includes an additional n-type gallium nitride clad layer 34 that provides a slightly better interface with the indium gallium nitride active layer 31; i.e. the adjacent GaN-InGaN layer tends to provide the opportunity for a higher quality interface than do adjacent AlGaN-InGaN layers. Figure 9 also illustrates an n-type aluminum gallium nitride layer 35 between the second gallium nitride layer 34 and the p-type aluminum gallium nitride layer 32. Finally, Figure 9 includes an additional p-type gallium nitride layer 36 as a top contact layer. This device offers the advantage of having the p-n junction 33 formed between adjacent layers of aluminum gallium nitride, and

the GaN layer 34 likewise provides a slightly better interface with the indium gallium nitride active layer 31 than does the AlGaN layer 32 of Figure 8.

Figure 10 illustrates the bandgap relationships of the embodiment of the present invention as illustrated in Figure 1 in which the n-type gallium nitride layer 30 (11 in Figure 1) is again a clad layer for the indium gallium nitride active layer 31 (13 in Figure 1). The opposing clad layer 36 is formed of n-type aluminum gallium nitride, and the device is completed with the p-type gallium nitride layer 36, thus defining the p-n junction 33 between the n-type AlGaN layer 35 and the p-type gallium nitride layer 36. This offers the advantage of having the p-n junction at the interface between the n-type aluminum gallium nitride 35 and the p-type gallium nitride 36. As noted above, other than an GaN-GaN junction, the AlGaN-GaN junction is the one most easily formed at the quality required for successful devices.

Figure 11 illustrates another embodiment of the present invention in which the first clad layer is the n-type gallium nitride layer 30, the active layer is indium gallium nitride 31, and the second clad layer is n-type aluminum gallium nitride 35. This embodiment, however, includes an additional layer of n-type gallium nitride 37 adjacent the n-type aluminum gallium nitride layer 35. As a result the p-n junction is formed between n-type gallium nitride 37 and p-type gallium nitride 36 giving a GaN-GaN interface that provides the highest quality from a structural standpoint.

Figure 12 illustrates another preferred embodiment in which the n-type gallium nitride layer 30 again forms one clad layer for the indium gallium nitride active layer 31. Similarly, the top contact layer is a p-type gallium nitride layer 36 as in Figures 10 and 11. As a clad and transition layer, Figure 12 includes the portion 40 that is progressively compositionally graded between n-type aluminum gallium nitride at the interface with the InGaN active layer 31 and substantially entirely n-type gallium nitride at the interface with the p-type gallium nitride layer 36. As a result, the p-n junction 33 is again made as a homojunction between the n-GaN portion of the graded layer 40 and the p-GaN layer 36.

The thickness of the layer or layers between the active layer and the p-n junction affects the functionality of the device. Layers that are too thin fail to offer the appropriate confinement, while layers that are too thick allow too much recombination to take place in the thick layer rather than in the active layer as desired. Accordingly, with respect to the embodiment depicted in Fig. 1, clad layer 12 should be between about 30 and 70 Å thick. With respect to the embodiment depicted in Fig. 3, clad layer 12 should be between about 20 and 50 Å thick, and layer 19 should be between about 30 and 50 Å thick. The total thickness of layers 12 and 19 should preferably be no more than about 100 Å. With respect to the efficiency of the devices, one goal is to minimize the nonradiative recombination current (J_{nr}) while maximizing the radiative combination current (J_r). In this regard, the

structure shown in Figure 8 has the greatest (i.e., least desirable) nonradiative recombination current. The nonradiative recombination current of the device of Figure 9 is somewhat less than that of Figure 8, but still greater than the more favorably lower nonradiative recombination current of Figures 10, 11 or 12.

In the drawings and the specification, typical embodiments of the invention have been disclosed. Specific terms have been used only in a generic and descriptive sense, and not for purposes of limitation. The scope of the invention is set forth in the following claims.